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TECHNIQUES FOR DETERMINING BUFFET ONSET

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Hampton, Va. 23365

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TECHNIQUES FOR DETERMINING BUFFET ONSET* **

By Edward J. Ray
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SUMMARY

An extensive study has been made by NASA to determine the extent and validity of buffet information which can be obtained during the course of conventional wind-tunnel testing.

Detailed comparisons have been made between wind-tunnel and flight results. This series of investigations, which has included studies of the F-111A, F-105F, F-4E, and F-8D configurations, has indicated that a thorough and systematic examination of several conventional wind-tunnel measurements can provide accurate and useful information regarding buffet onset and, in general, separation behavior. The studies, however, have substantiated that the experimental results which can be obtained from rigidly mounted wind-tunnel models should not be expected to provide quantitative amplitude and frequency characteristics, except possibly for using bending moments at the point of measurement.

INTRODUCTION

Buffeting is a vibratory phenomenon associated with the structural response of an aircraft to random excitations which occur in separated flow. The maximum capabilities of an aircraft could possibly be reduced by buffeting before the load limit, stall, or stability boundaries are reached by introducing vibrations which could affect such items as aircrew peace of mind and physical ability to accomplish specific tasks, disturbance of sensitive equipment, fatigue life, and in some cases, even structural integrity. The current requirements for advanced fighter airplanes necessitate the suppression of buffet to relatively high load factors, so that an accurate determination of buffet boundaries has become a paramount consideration in the preliminary design stages of certain aircraft.

For the past several years, NASA has been involved with a research program to assess aerodynamic approaches to alleviate the buffeting problem and to determine the extent and validity of the information which can be obtained during the course of

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**Title, Unclassified.

conventional wind-tunnel testing. ("Conventional" wind-tunnel tests are defined herein as those conducted with "rigid" force and pressure models as opposed to dynamically scaled, aeroelastic models.)

The purpose of this paper is to discuss (1) the significance of apparent intensity levels, (2) experimental techniques for determining buffet-onset characteristics, (3) the scope of investigation, (4) the interpretation of wind-tunnel results, (5) comparisons of wind-tunnel results with flight characteristics, and (6) factors affecting buffeting at high subsonic and transonic speeds.

SYMBOLS

α	angle of attack, deg
c	reference chord (see table I)
C_A	axial-force coefficient, $\frac{\text{Axial force}}{qS}$
C_L	lift coefficient, $\frac{\text{Lift force}}{qS}$
$C_{L,buf}$	lift coefficient for buffet onset
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{qSc}$
C_p	trailing-edge pressure coefficient
g	acceleration due to gravity
M	Mach number
M_{wsg}	averaged fluctuating wing bending moments root mean square
q	dynamic pressure
R	Reynolds number
S	reference area (see table I)
δ_{flap}	deflected trailing-edge flap
δ_{slat}	deflected leading-edge slat
Λ	leading-edge sweep angle, deg

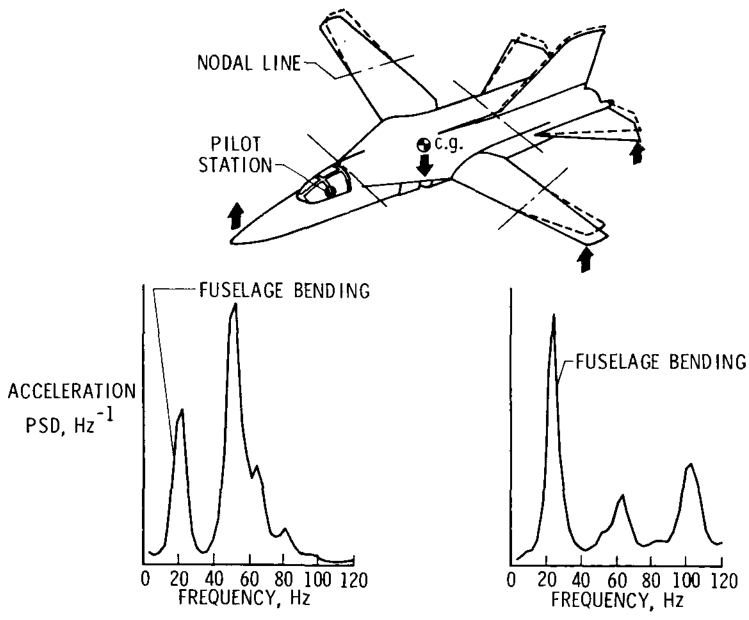
ABBREVIATIONS

c.g.	center of gravity
L.E.	leading edge
PSD	power spectral density
rms	root mean square
T.E.	trailing edge

DISCUSSION

Significance of Apparent Intensity Levels

Before the techniques and results of the so-called conventional investigations are reviewed, several factors should be considered with regard to the buffet behavior of the complicated structure of an aircraft. In figure 1 bending characteristics are shown for



(a) Pilot station, rms acceleration, 0.129g.

(b) Center of gravity, rms acceleration, 0.187g.

Figure 1.- Buffet response characteristics of a dynamically scaled aeroelastic model of the F-111A airplane. (Fuselage vertical bending frequency, 22.1 Hz.)

an aeroelastically and dynamically scaled F-111A model in one of the many modes of vibration. The fundamental-fuselage-bending frequency was selected for this illustration since a significant portion of the vibrations on the fuselage might be expected to occur at this frequency. The dash-dot nodal lines indicate the stations about which the various components vibrate, and the arrows illustrate the direction of the motions. As shown in the sketch at the top of figure 1, one nodal line is located slightly rearward of the pilot station. If the nodal line had coincided with the pilot station and the buffeting was reflected solely in this mode of vibration, no buffeting would have been perceived at the pilot station, even though the tail and wing tips were deflecting to large amplitudes. This was not the case; however, since the center of gravity as shown in figure 1 is considerably farther away from the nodal line than the pilot station, the buffet characteristics could not be expected to be the same at the two stations. The normalized power spectral density results shown at the lower portion of the figure were obtained from accelerometers located at the model pilot station and the center of gravity. The relative magnitude of the response in the fuselage frequency was considerably greater at the center-of-gravity station than at the pilot station. In addition, the rms accelerations of the two samples show that in this particular case the intensity level at the center of gravity was about 30 percent higher than at the pilot station. It may also be observed that the indicated relative importance of vibration modes contributing to the buffet response is a function of the location of the measurement.

The point to be made from the preceding discussion is that buffeting is an extremely complex, dynamic response which varies in amplitude and frequency at different locations on the aircraft. Wind-tunnel testing of rigidly mounted steel models, therefore, cannot be expected to provide quantitative amplitude and frequency results at remote locations on the fuselage of an aircraft. The remainder of the discussion is concerned with the sources and significance of buffet information which can be obtained during the investigation of rigid wind-tunnel models.

Test Techniques

Figure 2 indicates the techniques which have been evaluated in the present series of buffet studies. The models which have been studied incorporated steel wings, and no particular attention was given to the aeroelastic or dynamic similarity between the models and actual aircraft. As shown in figure 2, the approaches which have been considered included measurements of static forces and moments, wing-tip accelerations, and wing-root bending and visual flow observations.

These techniques may be considered to fall in the general categories of either aerodynamic or structural response indicators. The reliability of the aerodynamic indications of buffet onset is dependent upon the ability to detect flow separation from visual observations, pressure characteristics, or force and moment coefficients which might result in a

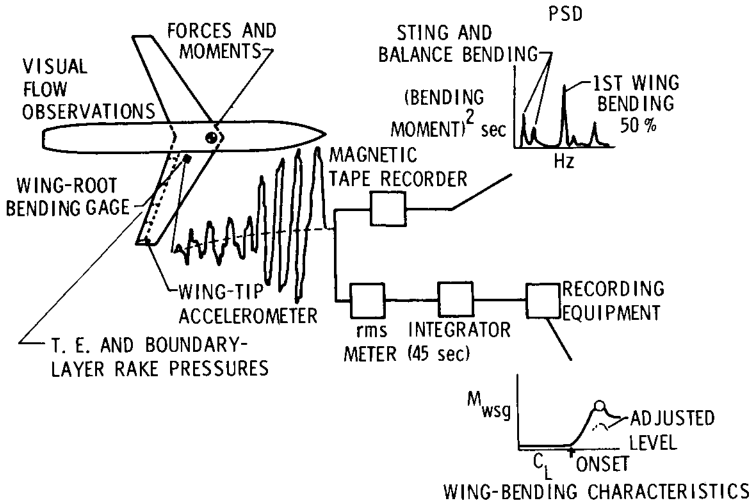


Figure 2.- Some techniques used to evaluate buffet characteristics.

significant vibration of the airframe. In the following sections of this paper specific examples will be cited to illustrate several difficulties which could be encountered in the interpretation of isolated aerodynamic trends under certain conditions of separation.

At the outset of these studies, a structural-response dynamic approach, such as the root-bending-gage technique, appeared to offer one of the most direct methods for determining buffet onset since the results might readily provide an integration of the effects of pressure fluctuations occurring over the entire wing panel. Past research has indicated that aircraft and wings of steel models sometimes exhibit a dynamic similarity which will permit the scaling of wing bending moments to flight conditions (ref. 1). These scaling procedures will not be discussed in detail; however, in essence it has been established that if the extraneous model responses such as support-system vibrations can be eliminated, the buffet intensity at the first wing-bending frequency of a steel wind-tunnel model sometimes can be adjusted and utilized to estimate flight buffet loads at the root of a wing. Although this type of buffet-load determination is difficult, the bending-gage method appeared to offer a suitable approach for buffet-onset determination.

The sketch shown at the lower right of figure 2 indicates that the alternating signals emitted from the bending gage were converted to root-mean-square values and then integrated for a selected sampling time. The M_{wsg} value then represents an average of the oscillating root-mean-square moments about a point near the wing root. The example which is shown in the figure illustrates that the rise in the M_{wsg} values above the tunnel turbulence level reflects the lift coefficient at which the wing vibrations increase and suggests the onset of wing buffet. Insofar as the development of a particular configuration for good high-lift characteristics is concerned, the information provided by the wing-root bending gage is certainly recognized as being inadequate to determine the type and location of flow separation and needs to be supplemented if possible by other information, such as pressure distributions and boundary-layer flow observations. In addition, past experience has shown that the bending-gage technique might not be suitable for all test facilities because of wind-tunnel turbulence and data-acquisition time. An effort was made, therefore, to examine all the techniques simultaneously to determine the reliability of the various buffet indicators.

Scope of Investigations

Table II indicates that the initial study consisted of a general research program (see refs. 2 and 3) which considered a number of geometric and test-condition variables. The purpose of this investigation was to evaluate the various buffet-determination techniques and to establish buffet-onset criteria which might be used in preliminary design considerations.

Because of current fighter-airplane requirements, the prediction of buffet onset has become a paramount consideration in the preliminary design stages of aircraft. Several investigations therefore were performed to provide additional information regarding the effects of specific wind-tunnel environments on the various types of buffet information. Numerous comparisons were made between wing-bending-gage results obtained in continuous-flow and blowdown tunnel facilities. A brief investigation was made with the general research model in a variable-pressure tunnel to determine the effect of Reynolds number on buffeting at a given Mach number. Variations in tunnel power settings and tunnel test-section configuration were studied to obtain an indication of the extent of the influence of tunnel noise on the "aerodynamic and structural response indicators" displayed by a particular configuration mounted on a specific support system in the same test section.

A limited number of studies were accomplished to evaluate the influence of external stores on aircraft buffeting. For these studies, a variable-sweep fighter model was tested, and the variations which were studied included wing sweep, Mach number, and the locations of the stores.

In support of the development of the advanced fighter airplanes, the F-14 and F-15, several of the proposed concepts were evaluated from a buffet standpoint to assess the effects of items such as Mach number, artificial transition-strip location, leading- and trailing-edge flap devices, and wing geometry.

Throughout the program, attempts were made to obtain wind-tunnel data which could be compared with flight results. The correlations between wind-tunnel and flight results which have been considered thus far have included the F-111A, F-105F, F-8D, and F-4E configurations.

A thorough presentation of all the results determined in this rather extensive series of buffet studies would be extremely lengthy. Therefore, the following discussion is limited to correlations between flight and wind-tunnel results to indicate the techniques and degree of interpretation involved in analyzing the various aerodynamic and structural response characteristics determined in the wind tunnel.

Comparison of Wind-Tunnel Results With Flight Data

Wind-tunnel and flight results which were determined for the F-111A configurations are illustrated in figure 3. Lift coefficients for buffet onset are plotted against Mach number for wing-sweep angles of 26° and approximately 72°. The onset conditions which were obtained in the wind tunnel for a 1/24-scale model (see ref. 3) and a 1/15-scale model are depicted by the solid and dashed lines. (The model onset conditions in this case were determined from a composite examination of wing-bending-gage results and static force and moment characteristics.) The symbols represent the flight conditions at which definite oscillations were visible from accelerometer (located near the center of gravity) and wing-bending strain-gage traces (refs. 4 and 5). It will be noted from this summary figure that for a wing sweep of 26° at subsonic Mach numbers, an excellent correlation generally exists between the wind-tunnel and flight results. Figure 3 shows also that for a wing sweep of 26° at high-subsonic Mach numbers, where a transition from subsonic to a "mixed" (transonic) flow condition would be expected to occur, the wind-tunnel results suggest a buffet "buildup" or buffet development region rather

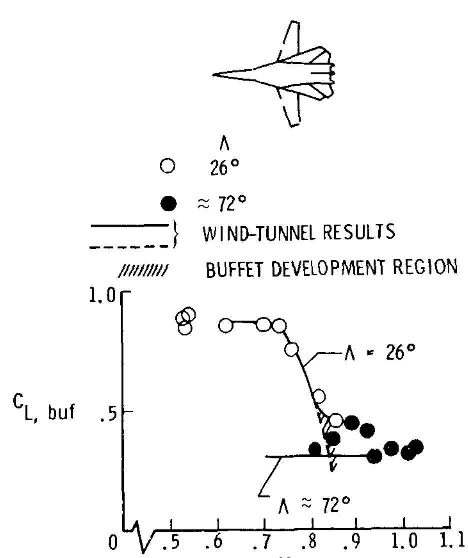


Figure 3.- Comparison of buffet-onset lift coefficients obtained from wind-tunnel and flight tests for the F-111A airplane.

than an isolated, precise, onset point. This phenomenon will be considered in more detail in the discussion of figure 4. The results shown for the sweptback ($\Lambda \approx 72^{o}$) configuration indicate that in general, an encouraging correlation exists between the flight and wind-tunnel results. (See ref. 5.)

Three samples of the wind-tunnel results which were utilized to determine the F-111A buffet-onset conditions are shown in figure 4 for a 1/15-scale model to illustrate the behavior of the commonly used buffet indicators under different conditions of separation. At the left of the figure, results are shown for a Mach number of 0.70 and a wing sweep of 26^{o}. Fluctuating root-bending moments, pitching-moment coefficients, axial-force coefficients, and lift coefficients are illustrated as a function of angle of attack. The dashed axial-force curve shown in the illustration and subsequent figures represents the theoretical axial-force variations which were developed from lifting-surface theory and recent technology on leading-edge suction (refs. 6 and 7). At a Mach number of 0.70 the angle of attack for buffet onset in flight (illustrated by the dashed vertical line) corresponds almost exactly with the divergence in the bending-moment responses and the departure of the experimental axial-force variation from the theoretical results. The axial-force variation has been found generally to provide a good indication of buffet onset and the progression of separation. For instance, the example cited here represents the rather classic axial-force reversal due to an abrupt loss of leading-edge suction which is typical for comparatively thick, low-sweep, high-aspect-ratio wings. The axial-force indication is not always this straightforward; however, as long as near-theoretical suction values are developed, the wing will not buffet. In this example, where the buffeting of the airframe probably occurs as a result of a pronounced stall, the break in the lift and pitch curves corresponds almost exactly with the onset point.

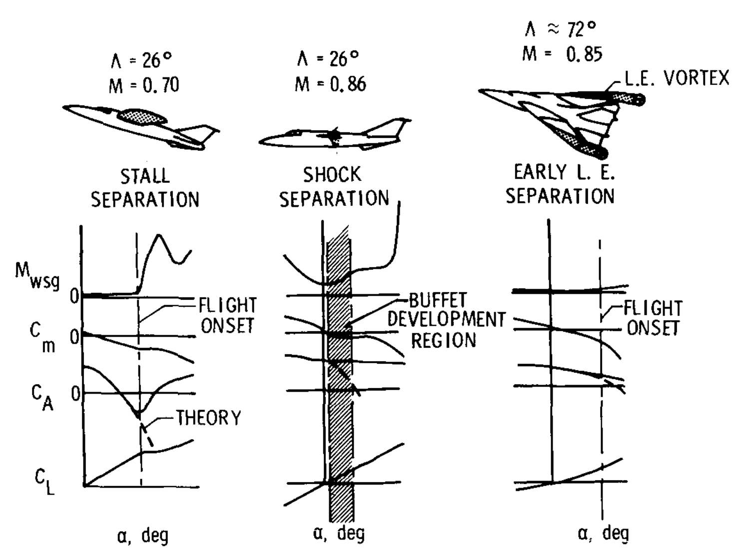


Figure 4.- Comparison of various wind-tunnel buffet-onset indications (1/15-scale model) with flight data for the F-111A airplane.

In some situations at transonic Mach numbers an apparent buffet will occur at all lift coefficients. As an example, the wind-tunnel results which are shown in figure 4 for the F-111A configuration at a Mach number of about 0.86 and a wing sweep of 26° indicate a noticeable increase in the bending moments at small plus or minus angles of attack. Only small variations are noted in the axial-force variation, and the pitching-moment and lift-coefficient variations indicate significant nonlinearities at low lifts.

It is suspected that the low-lift divergences reflected in the static-aerodynamic and bending-gage curves are indicative of a shock development on the comparatively thick, low-sweep wing. If the conservative approach is taken, such as that described in reference 2, then it would be concluded that the mechanism (i.e., separation) required to cause buffet is present at a very low lift coefficient as shown in figure 3 by the dashed line. However, the significance of this low-intensity buffet at the center of gravity or pilot station of the aircraft cannot be ascertained from the characteristics displayed by a rigidly mounted conventional wind-tunnel model.

It is also shown in figure 4 that for a Mach number of 0.86 and a wing sweep of 26°, the second series of divergences which occur at a higher angle of attack correspond closely to the condition recorded for the F-111A airplane in a buffet study at the NASA Flight Research Center (ref. 5). This second series of divergences is believed to be associated with a more pronounced separation which occurs as a result of the high angularities of the airflow over the wing. The shock-induced boundary at low angles of attack and the pronounced boundaries at higher angles of attack both are believed to be present in the actual flight environment, although this is not entirely conclusive from correlations between flight and wind-tunnel buffet studies made thus far. The determination of the onset condition in flight however is dependent upon the location of the measurement and the predetermined level selected for defining buffet onset. For example, in the F-111A flight tests (ref. 5), the general rule for onset was a normal peak-to-peak acceleration of approximately 0.06g near the airplane center of gravity, which could be under certain conditions of frequency an unacceptable motion. If for instance, the criterion for onset had been established as a peak-to-peak acceleration of 0.02g, the onset undoubtedly would have occurred at a lower lift coefficient. This might possibly substantiate the lower, more conservative boundary suggested by the wind-tunnel results shown in figure 3 and unpublished pilot-opinion results.

The two cases of divergences which have been cited illustrate the behavior of a particular configuration as a result of stall and shock-induced separation. The sweptback F-111A serves to illustrate another type of separation which is typical of highly swept, low-aspect-ratio wings. The results at the right of figure 4 for a wing sweep of approximately 72° and a Mach number of 0.85 show that it would be difficult to assess the onset condition from any one of the four characteristics; however, a simultaneous examination of all the characteristics provides a better estimate of the onset point. For the low wing sweep it was shown that the angle of attack at which the lift-curve slope diminished was related to the onset of buffeting in flight. But for the highly swept wing, the onset point is associated with an increase in the lift-curve slope. The sketch shown at the upper right of figure 4 illustrates that the flow over the highly swept wing is characterized by a spiral vortex system resulting from leading-edge separation. Low-energy air is bled off the wing through the vortex core, and the vortex action results in reattached flow inboard of the leading-edge vortex. This type behavior results in a stable flow condition, an increase in lift-curve slope, and a very gradual progression in the extent of the separation.

Results for the F-8D which were obtained in flight and in the wind tunnel (ref. 8) are presented in figure 5 at the top of the figure. The wind-tunnel results are shown by the circular symbols and the flight results are indicated by the solid line. It will be noted that as in the case of the F-111A configuration, an excellent correlation was obtained between the flight results (obtained from accelerations at the center of gravity) and the wind-tunnel results. The bending-gage results and static-force coefficients included in figure 5 were analyzed in the manner previously discussed for the F-111A. In addition to these data, trailing-edge pressure characteristics were obtained for the F-8D model. At a Mach number of 0.75 the pressure coefficients shown in figure 5 indicate an early separation at the tip before the onset point; the separation appears to progress inboard as angle of attack is increased. The pressure results for a Mach number of 0.91 indicate that the initial separation occurs near the wing root rather than at the wing tip. Trailing-edge pressure characteristics as shown here are sometimes sensitive to unusual flow conditions and spanwise location. Useful information as to the location and extent of the initial separation, however, can be derived from pressure characteristics.

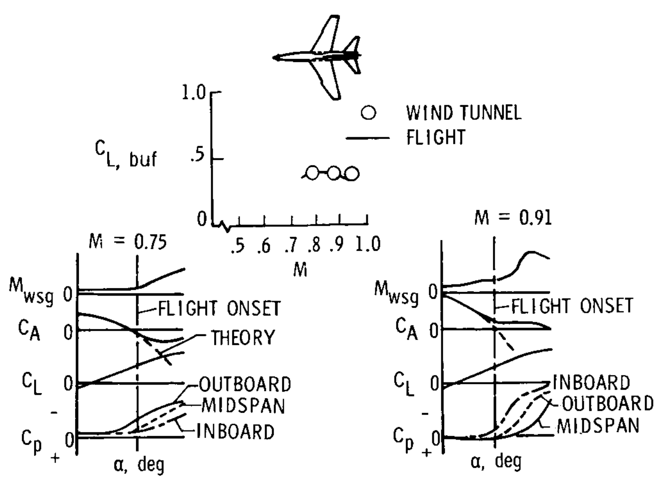


Figure 5.- Comparison of various wind-tunnel buffet-onset indicators (1/22-scale model) with flight data for the F-8D airplane.

Buffet Improvement Studies

The results which have been obtained in this series of investigations have emphasized the definite relationship which exists between buffet onset and other aerodynamic characteristics. Similar to the performance situation, the design requirements for good subsonic characteristics tend to conflict with transonic requirements. The ideal approach would naturally be to suppress separation to lift coefficients beyond the operating range through the incorporation of advanced airfoil designs or the use of variable-geometry airfoil devices. Figure 6 presents the results of unpublished wind-tunnel studies which illustrate the effects of several approaches which have been taken to improve the buffet characteristics of three current fighter configurations. The lift coefficients for buffet onset have been plotted as a function of Mach number for F-105F, F-4E, and F-111A models. The solid lines in all three cases indicate the results obtained for the basic configurations. The dashed lines illustrate the onset conditions determined for the F-105F with deflected leading- and trailing-edge flaps, the F-4E configuration with leading-edge devices, and the F-111A with an extended trailing-edge flap. The dash-dot line shown for the F-111A indicates results which were obtained with a supercritical airfoil. The F-105F and F-4E results show that incorporation of the wing devices resulted in sizable increases in the lift coefficients for buffet onset. Recent flight tests have substantiated the wind-tunnel findings. The F-111A results indicate that substantial improvements can be obtained by incorporating a trailing-edge flap system. The utilization of supercritical airfoil sections with the basic F-111A wing planform produced an even more dramatic effect (ref. 9). It can be seen from the curve at the top of the figure that buffet-free lift coefficients greater than 0.9 were achieved throughout the transonic Mach number range. At present, a transport-configured supercritical wing is being developed for application to an F-8 fuselage for proof-of-concept flight tests.

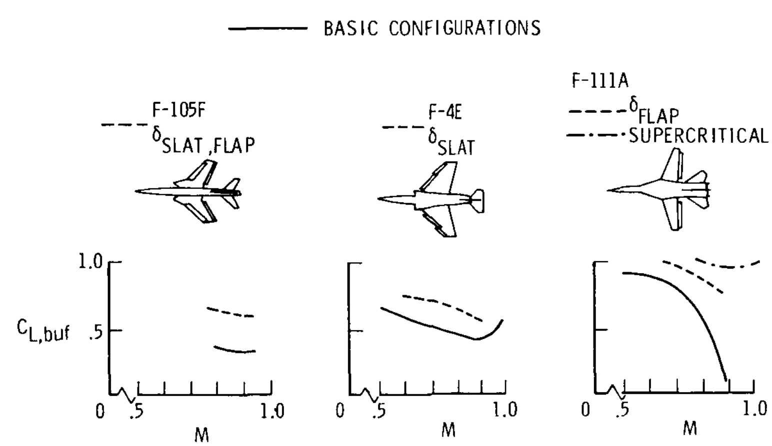


Figure 6.- Buffet improvement studies.

Factors Affecting Wind-Tunnel and Flight Correlations

It has been shown in the preceding figures that the buffet-onset comparisons which have been made in this series of studies have indicated meaningful correlations between flight and wind-tunnel results. Explainable differences have been observed during this research between flight and wind-tunnel results which should be noted in this discussion.

In certain isolated cases buffet onset has been shown to be affected by the position of artificial transition strips, and it appears that in order to simulate flight buffet conditions properly, the flight boundary-layer thickness at the trailing edge of the wing should be duplicated (ref. 10). Also, on several occasions (for instance, see ref. 11), the apparent onset point at a given Mach number appeared to be delayed with increases in altitude. This apparent effect has been noted in several flight tests and the largest differences have been reflected in the pilot's perception of the initial buffet. One possible explanation is that at the higher altitudes, the rise in buffet intensity with increasing angle of attack would tend to be less abrupt than at lower altitudes. With a marked decrease in the intensity slope, the actual onset point (i.e., the point at which flow separation and pressure fluctuations commence) could occur before the perception level of the pilot or the predetermined intensity level for "onset" sensed by the various test instruments is reached. The decrease in the flight buffet intensity slope at the higher altitudes is analogous to situations which have been observed in the wind tunnel with reductions in dynamic pressure and density.

Finally, in the F-8D tests an excellent correlation was obtained between the onset conditions determined in the wind tunnel and in flight at the airplane center of gravity. The flight onset conditions determined at the pilot station, however, occurred at higher lift coefficients than at the airplane center of gravity. In the discussion presented earlier, it was shown that because of the complicated structure of an aircraft, the structural responses reflected at various fuselage stations differ in amplitude and frequency content. The perceptible level of buffeting, therefore, could be reached at the center of gravity before the pilot station.

CONCLUDING REMARKS

Although it has been shown that misleading conclusions can be drawn from wind-tunnel results, this series of investigations has indicated that a thorough and systematic examination of data characteristics from "conventional" wind-tunnel investigations can provide accurate and useful information regarding buffet onset and, in general, separation behavior.

With regard to buffet requirements for specific aircraft, positive definitions should be established to indicate the significance of buffeting in terms of location, amplitude, and frequency. For example, a fluctuation of $\pm 0.05g$ may be intolerable to a pilot or sensitive equipment at the lower frequencies but might not be perceptible at 100 Hz.

At present the approaches available for determining buffet accelerations and amplitudes are lengthy and difficult, and probably could not be undertaken in the preliminary design stages of an aircraft. Endeavors should be continued, therefore, to simplify and refine the approaches for determining buffet intensity characteristics.

Researchers should continue to emphasize the development of advanced airfoils and wing devices to suppress separation to higher lift coefficients.

Finally, since even the well-defined buffet and lift boundaries will be exceeded under certain flight conditions, preliminary design studies should consider stability and control behavior in separated flow environments.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 31, 1970.

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TABLE I.- REFERENCE AREAS AND CHORDS

Configuration	Reference area, S		Reference chord, c	
	ft^2	m^2	in.	cm
1/15-scale F-111A	2.333	0.217	7.234	18.374
1/24-scale F-111A	0.911	0.085	4.521	11.483
F-8D	0.662	0.062	5.938	15.083
F-4E	1.325	0.123	9.624	24.445
F-105F	0.795	0.074	6.264	15.911

TABLE II.- SCOPE OF BUFFET RESEARCH PROGRAMS

Test	Variables
General research program	M, R, section and planform geometry, wing position, L.E. and T.E. flaps, fuselage shape, transition location
Wind-tunnel calibration models	Wind-tunnel configuration
Effect of external stores	Store configuration and location
Advanced-fighter concept	M, transition location, section geometry, flap effects
F-111A (1/24- and 1/15-scale models) F-111A flight (FRC)	M, section geometry, flap effects M and altitude
F-105F (1/22-scale model) F-105F flight (USAF)	M, transition location, flap effects M, altitude, flap effects
F-8D (1/24-scale model) F-8D flight (LTV)	M M and altitude
F-4E (1/24-scale model) F-4J flight (McDonnell Douglas)	M, transition location, leading-edge flap M

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16. Abstract

An extensive study has been made by NASA to determine the extent and validity of buffet information which can be obtained during the course of conventional wind-tunnel testing.

Detailed comparisons have been made between wind-tunnel and flight results. This series of investigations has indicated that a thorough and systematic examination of several conventional wind-tunnel measurements can provide accurate and useful information regarding buffet onset and, in general, separation behavior. The studies, however, have substantiated that the experimental results which can be obtained from rigidly mounted wind-tunnel models should not be expected to provide quantitative amplitude and frequency characteristics, except possibly for wing bending moments at the point of measurement.

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